


Integrating local knowledge with tree diversity analyses to optimize on-farm tree species composition for ecosystem service delivery in coffee agroforestry systems of Uganda

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Abstract Coffee agroforestry systems deliver ecosystem services (ES) critical for rural livelihoods like food but also disservices that constrain livelihoods like fostering coffee-pests. Since such ES are tree-based, maximizing ES and limiting constraints requires knowledge on optimizing on-farm tree composition especially trees adapted to local conditions. The study was in three sites along a rainfall gradient in Central Uganda where we: assessed tree diversity in coffee agroforestry; ranked tree suitability for providing ES according to farmers' knowledge; and then proposed an approach for optimizing on-farm tree composition for delivery of ES. We collected data on tree diversity and, farmers' knowledge of tree species and the ES they provide. Farmers ranked ES in order

of importance to their livelihoods ('Needs rank') and ranked trees according to suitability for providing ES. Using Bradley Terry modeling, we grouped trees into 'ES groups' according to suitability for providing different ES and ranked 'ES groups' according to tree diversity ('Diversity rank'). Tree-suitability for providing ES and importance of ES to farmers varied with rainfall regime but tree diversity did not match farmers' needs for ES. We propose the FaD–FaN (matching farm tree diversity to farmers' needs) approach for optimizing tree species composition with respect to tree-suitability for farmers' priority ES. Farmers locally prioritize ES needed and identify trees that best serve such ES. The approach then focuses on modifying on-farm tree diversity to match/suit

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farmers' priority ES. The FaD–FaN approach caters for varying socio-ecological conditions; it's adaptable for other coffee and cocoa-growing areas worldwide.

Keywords Coffee · Shade trees · Tree diversification · Farmers' knowledge · Farmers' needs · Climate Change

Introduction

Globally, areas suitable for coffee production will shrink up to 40% if temperatures increase by 2 °C by 2050 and 4 °C by 2100 (IPCC 2014; Adhikari et al. 2015). Coffee production will remain possible in some areas of East Africa but sustaining or improving upon current levels of production will require adaptation (Bunn et al. 2015). A commendable adaptation option is the promotion of agro-biodiversity and delivery of ecosystem services (ES) from ecosystem-based adaptation practices (Noordwijk et al. 2011). Ecosystem-based adaptation practices can deliver an optimized set of ES that can support farmers to adapt to, and mitigate climate change effects and improve livelihoods: The most promising ecosystem-based adaptation practice in coffee production is agroforestry (Vignola et al. 2015). However, not all agroforestry options fit everywhere (Coe et al. 2014). Moreover, the current state of knowledge fails to demonstrate how to optimize delivery of ES through agroforestry (Mbow et al. 2014a). Optimizing ES delivery is critical for context-specific agroforestry options including synergies between climate change mitigation and adaptation (Rahn et al. 2014; Vaast et al. 2016). Since biodiversity underpins ES delivery (Cardinale et al. 2012), targeted changes in tree diversity can influence ES derived from coffee agroforestry (Cardinale et al. 2011; de Beenhouwer et al. 2013). We hypothesize that farms should have more tree diversity—hence more functional stability (Leary and Petchey 2009; Mori et al. 2013)—targeted to deliver priority ES. This study proposes an approach for optimizing on-farm tree composition for ES delivery. The study: assessed tree diversity in coffee farms; used farmers' knowledge to evaluate tree suitability for providing ES; and proposes an approach for optimizing on-farm tree

composition to deliver a locally-adapted set of ES that meets farmers' prioritized needs.

Methods

Site description

The study covered the greater Luweero region (Fig. 1) of Central Uganda (between 31°E–32°E and 0.5 N–1.3°N) with an area of approximately 9000 km². The greater Luweero region receives a bimodal rainfall with peaks in March to May and October to November. Annual rainfall varies from 700 mm in the North up to more than 1300 mm in the South (Lwasa et al. 2011; Funk et al. 2012). Consequently, the rainfall gradient was divided into three zones: a high rainfall zone (> 1300 mm), a moderate rainfall zone (1100–1300 mm) and a low rainfall zone (< 1100 mm). Across the rainfall gradient, most of the Robusta coffee is grown in CAFS. The present study used this rainfall gradient as a proxy for a climatic gradient to generate insights into possible climate change effects on tree suitability for ES.

Data collection

Stratified random sampling was used to select study farms where rainfall zoning was the stratum and within each rainfall zone, we randomly chose 100 coffee farming households totaling to 300 households that we studied in two phases. In phase one, we randomly selected 150 coffee farming households (50 per rainfall zone) and collected tree diversity data from their coffee farms through tree-inventories. During the inventories, we identified tree species by local names in Luganda (Language in central Uganda) and corresponding botanical names from tree identification guides e.g., Katende et al. (1995). For every tree species encountered, we made a technical sheet with photos showing its bole, fruits, leaves, branching, flowers, bark, and local names. In phase two, we conducted a cross-sectional household survey of 300 coffee farming households (including 150 of phase one) and assessed farmers' local knowledge of trees using ranking interviews. The interview had two stages. First, we presented farmers with 12 tree-based ES that they consider key services for their livelihoods: coffee yield increase (some trees associated

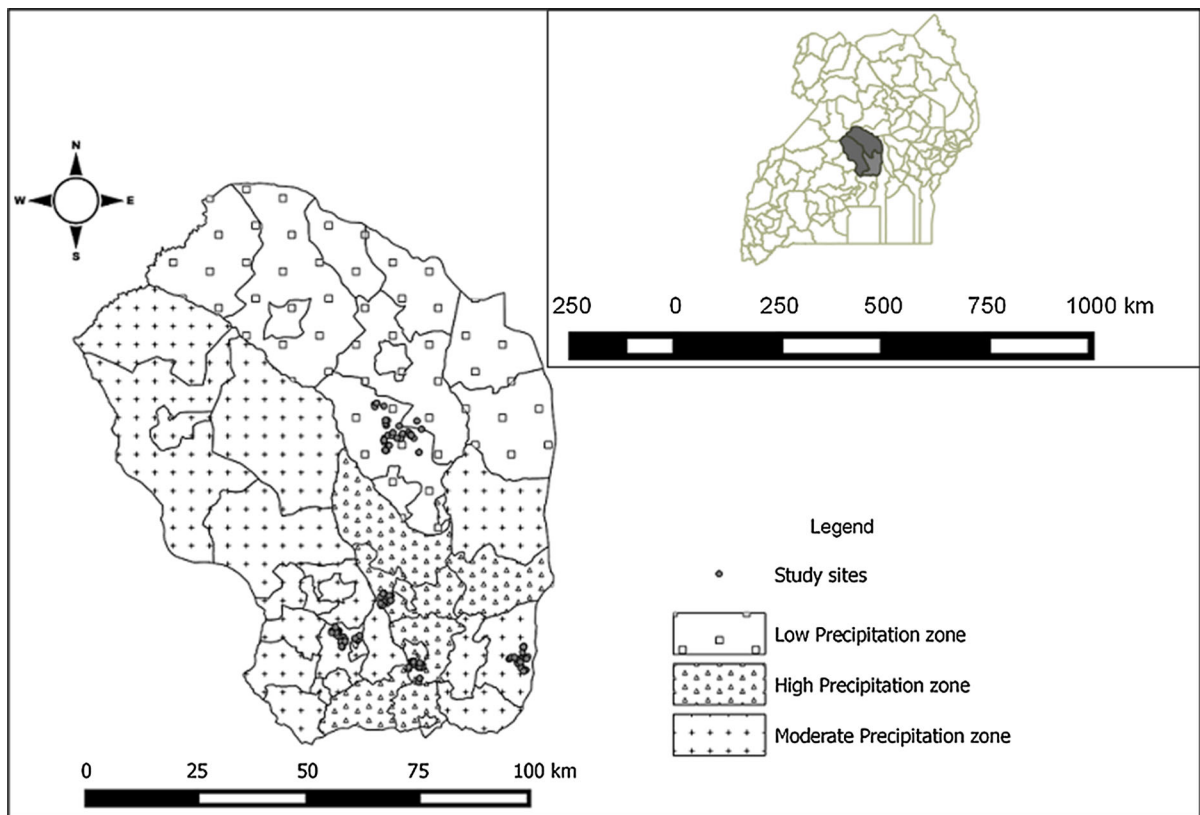


Fig. 1 Map of study area showing the Luweero region and the different rainfall (precipitation) zones of the study area

with increased coffee yield); soil moisture preservation (some trees associated with soil water conservation); leaf litter provision (some trees drop a lot of litter); tree leaf decomposition (some tree-leaves decompose fast); food provision (some trees have edible parts); provision of quality shade for coffee (some trees have better shade for coffee); microclimatic temperature buffering (some trees cool the microclimate more than others); suppression of major coffee pest—*Xylosandrus compactus* (some trees are associated with the pest); weeds suppression (some trees suppress weed growth); fuel wood provision (some trees provide better firewood); tree growth rate (some trees grow faster) and timber provision (some trees provide better timber). Each farmer ranked these ES according to importance to his/her livelihood needs. Second, we presented each farmer with technical sheets (visual aided tree representations for all tree species) of the 20 most abundant trees in his/her respective rainfall zone; and asked him/her to select 10 tree species that he/she knew best. Each farmer ranked his/her selected 10

trees in order of suitability for providing each of the 12 ES. The ranking was visually aided by technical sheets (as a representation of tree species) that farmers arranged from most to the least suitable tree for providing an ES: ranking one ES at a time until farmers completed ranking trees for all the 12 ES (Elliott 2009).

Data analysis

Tree species richness and abundance among rainfall zones

To determine tree species richness among rainfall zones, we analyzed tree inventory data using Estimate S software version 9 (Colwell 2013). We present the four (Chao 1, Chao 2, Jack 1 and Jack 2) most precise, accurate, robust and unbiased species richness estimators (Walther and Moore 2005; Chiarucci 2012). To compare species richness among rainfall zones, we used species accumulation curves scaled by individuals (Chazdon et al. 1998; Gotelli and Colwell 2001)

and extrapolated with 95% confidence boundaries (Shen et al. 2003) until the most species-rich sample reached an asymptote (Colwell et al. 2012). Species richness is significantly different between zones if respective confidence boundaries at asymptote do not inter-cross each other. To determine species similarity among rainfall zones, we used Bray–Curtis (BC) abundance-based similarity index (Bray and Curtis 1957). BC index value ranges from zero (perfectly similar) to one (perfectly dissimilar). We used rank abundance curves to determine the most abundant set (20 species) of trees in each rainfall zone that represented over 90% of tree diversity.

Farmers' local knowledge of coffee-shade trees

We analyzed farmers' ranking of (i) ES and (ii) trees for providing ES at plot level; using Bradley and Terry (BT) model (Bradley and Terry 1952) in 'BradleyTerry2' package of R (Turner and Firth 2012; R Core Team 2015). The model based on how various farmers ranked trees for ES provision to generate a score upon which it ranks the trees. The scores are, however, not absolute and are only meaningful relative to one another and can take on any value from negative to positive infinity but the magnitude between score is absolute and does not change. To simplify comparisons, we shifted/transformed results to get the lowest score to zero so as to yield positive scores only. The difference between scores of individual trees determines the probability of ranking one tree above another in the final output. BradleyTerry model also produces a confidence interval for each score that reflects the ranking frequency of that tree. Larger confidence intervals show trees selected rarely for ranking and ranked less concordantly. The model output is a graph showing the final rank order of tree species and associated confidence interval based on model-generated scores. The rank order shows farmers' ranking of how suitably trees deliver ES at the plot level, i.e., from the most to the least suitable tree for a particular ES. To allow flexibility and avoid recommending only one tree per ES; we applied a set of rules to determine the best (top) performing group of trees for each ES:

- i. The top group should have at least four tree species.
- ii. If the lower boundary of the confidence interval of current ranked item is lower than

the score of the next ranked item, then those items belong to the same group. If the lower boundary of the confidence interval of the current ranked item is higher than the score of the next ranked item then such items belong to different groups.

- iii. If the tree right next to the topmost group is a lone group member (occurs alone in its group), it is adjoined to the topmost group. The most suitable (top) groups of trees for various ES are herein referred to as the ES groups of trees.

Relating diversity rank to 'Needs rank' of ecosystem service groups

'Diversity rank' here means the ordering of ecosystem-service groups of trees from one with highest tree diversity to one with lowest tree diversity. To order ES groups according to diversity, we used a Rényi diversity profile (Rényi 1961; Tóthmérész 1995; Lövei et al. 2013). Rényi diversity profile values were calculated in R statistical software (R Core Team 2015) with package Biodiversity R (Kindt et al. 2015). If the profile of group A is above the profile of group B at all Rényi values, then group A is more diverse than group B. If the profile of group A inter-crosses that of group B, the two groups cannot be ordered (Kindt et al. 2006). In this case, we revert to the less strict approach of a single diversity index, Shannon diversity index, to derive the 'Diversity rank'. We derived Shannon diversity index from, and when the Rényi value approaches one (Kindt et al. 2006). The 'Needs rank' means the ordering of ES groups from most to least important as ranked by farmers and analyzed using BT model. We examined the correlation between 'Diversity rank' and "Needs rank" using Spearman's rank correlation test (Höft et al. 1999).

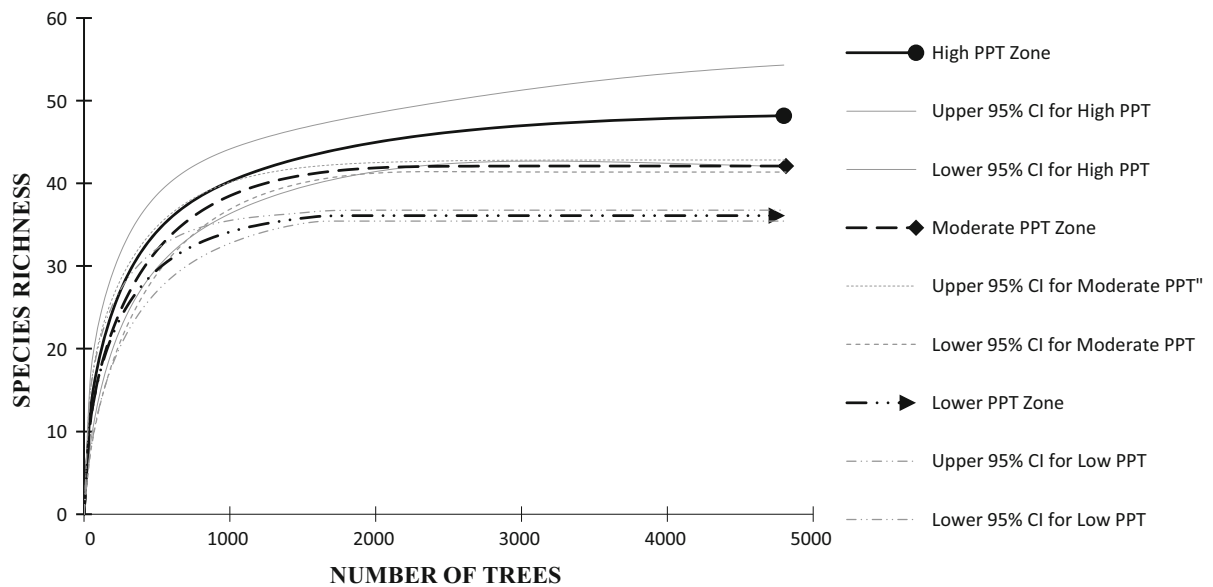
Results

Tree species composition and diversity

The study recorded 1604 trees in low rainfall zone, 2196 trees from moderate rainfall zone and 2009 trees in high rainfall zone. Tree-species richness ranged from 29 species ha⁻¹ in low rainfall zone to 39 species ha⁻¹ in high rainfall zone (Table 1). The low rainfall

Table 1 Species richness for the three rainfall zones of Central Uganda, based on four non-parametric species richness estimators and their standard errors in parentheses

Rainfall zone	Trees	Genera	Families	Species ha ⁻¹	Chao 1	Chao 2	Jack 1	Jack 2
High	2009	42	28	39	46.51 (2.13)	49.92 (4.76)	51.98 (3.18)	54.17 (6.64)
Moderate	2196	35	24	35	42 (0.12)	42 (0.08)	42.98 (0.98)	39.21 (0.00)
Low	1604	37	20	29	36.11 (1.5)	36.93 (2.22)	38.74 (1.98)	39.06 (4.17)

**Fig. 2** Species accumulation curves and associated bootstrap confidence boundaries for the three rainfall zones. If the lines showing confidence boundaries for different rainfall zones cross

each other, species richness in the two rainfall zones is not significantly different (PPT zone = rainfall zone)

zone had the lowest number of tree species, genera and families while high rainfall zone had the highest number of tree species, genera and families (Table 1). Species richness varied among rainfall zones in a pattern similar to that of taxonomic groups (Fig. 2). There was low species similarity among rainfall zones but low and high rainfall zones showed higher similarity ($BC = 0.670$) than between moderate and low ones ($BC = 0.685$) and between high and moderate rainfall zones ($BC = 0.812$). In each rainfall zone, about the top 20 tree species constituted about 90% of total tree abundance (Fig. 3). Consequently, only the most abundant 20 species were used in the ranking exercise for each rainfall zone.

Farmers' local knowledge of trees and ecosystem services

Farmers ranked 12 ES according to their farm and livelihood needs in each rainfall zone (Fig. 4). Generally, the importance of tree-ecosystem services to farmers differed among rainfall zones. For instance, the importance of shade quality and leaf litter provision increase but the need to suppress black coffee twig borer reduces from high to low rainfall zones. However, some ES were equally important in all rainfall zones. For example, farmers ranked soil moisture preservation and yield increase in the top three ES in all rainfall zones. For every ES considered, we determined a group of trees that farmers think that are the best at providing that service (Table 2). For example, Fig. 5 shows the ranking of trees suitable for

Fig. 3 Rank abundance curves of agroforestry tree species in Luweero. Each line represents one rainfall (precipitation) zone. Tree ranking order is based on abundance. From most to least abundant tree

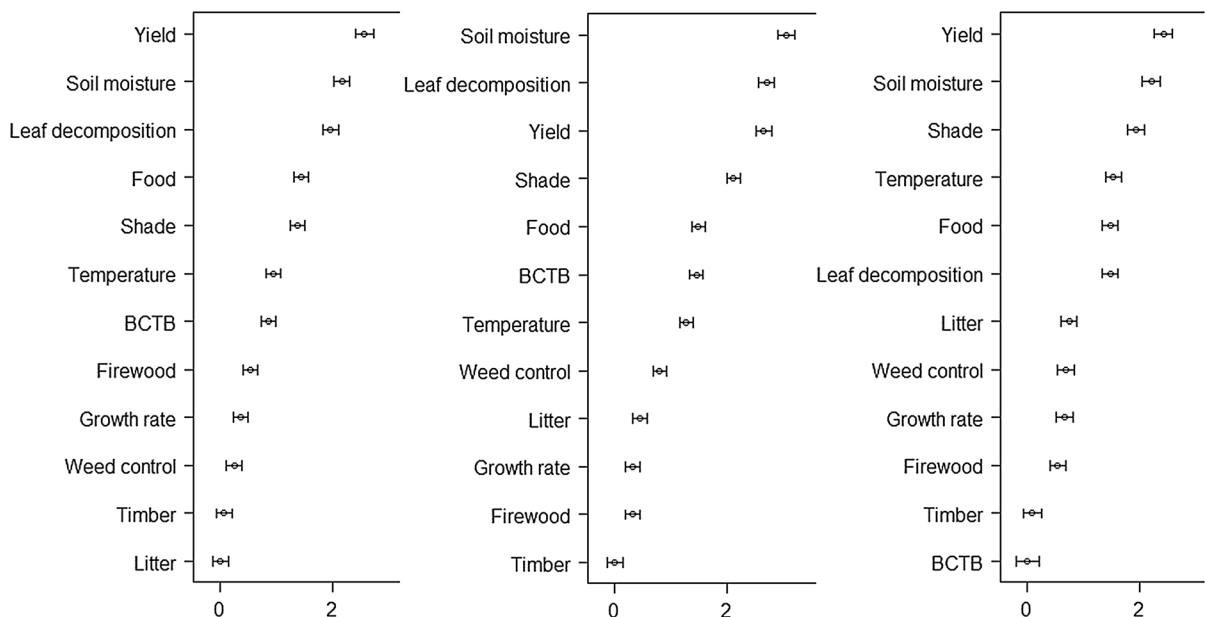
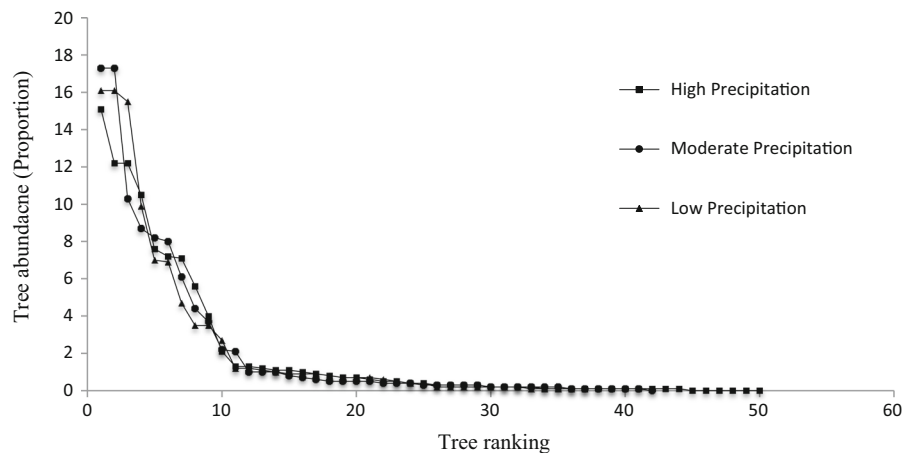


Fig. 4 Farmers' ranking of the priority ecosystems services provided by trees on coffee farms according to order of importance in different rainfall zones, i.e., Needs rank for each rainfall zone. From left to right: high, moderate and low rainfall zones

shade quality for coffee and the most suitable tree species (top group) are marked with a rectangle. According to farmers' knowledge, this top group forms the ES group of tree species for shade quality in high rainfall zone. Trees were also not limited to serving one ES. According to farmers, the most multipurpose trees were: *Albizia coriaria* Oliv, Fabaceae family, suitable for 9 out of 12 ES in all rainfall zones and *Ficus natalensis* Hochstetter, Moraceae family, suitable for 8 out of 12 ES in all rainfall zones. The least multipurpose trees were

Annona muricata, Annonaceae family, and *Grevillea robusta*, Proteaceae family, as they each served only one ES in one rainfall zone but ranked highly for the respective ES they served.

Relating on-farm tree diversity to farmers need for ecosystem services

This study determined farmers' ranking of ES (Needs rank) from most to least important for their livelihoods (Fig. 4) across rainfall zones. The study also used tree

Table 2 Agroforestry trees ranked by farmers according to their suitability to provide ES in different rainfall zones of Central Uganda; trees listed directly below each ES (Ecosystem Services) are suitable for that ES in all rainfall zones

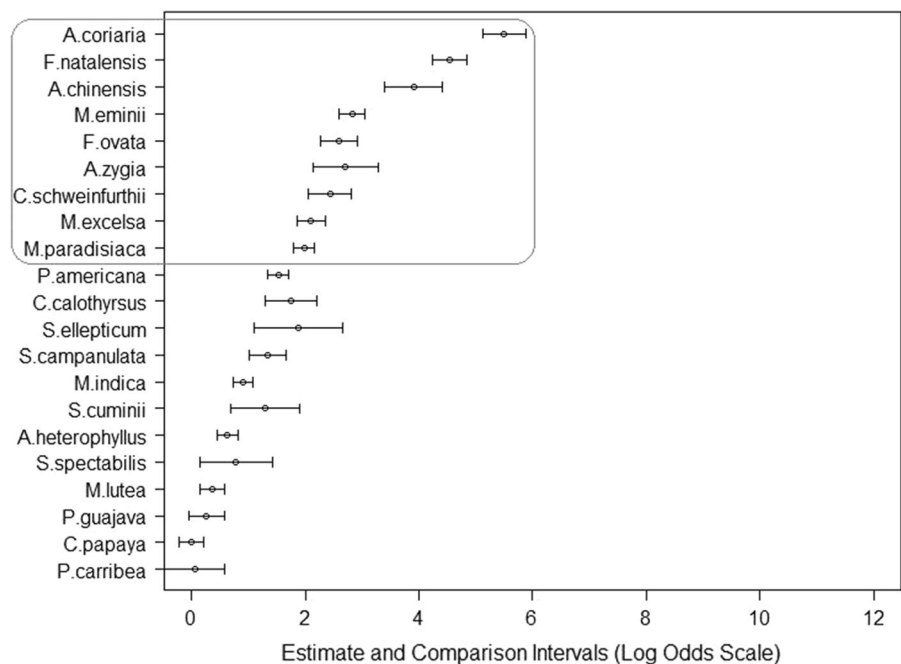
Ecosystem service	High PPT zone	Moderate PPT zone	Low PPT zone	Ecosystem service	High PPT zone	Moderate PPT zone	Low PPT zone
Amount of litter				Shade quality			
<i>Artocarpus heterophyllus</i>	<i>Ficus natalensis</i>	<i>Ficus natalensis</i> <i>Albizia chinensis</i>	<i>Ficus mucoso</i>	<i>Albizia coriaria</i>	<i>Albizia chinensis</i> <i>Albizia zygia</i>	<i>Albizia chinensis</i>	<i>Ficus mucoso</i> <i>Spathodea campanulata</i>
<i>Mangifera indica</i>		<i>Milicia excelsa</i> <i>Ficus ovata</i>		<i>Ficus natalensis</i>	<i>Canarium schweinfurthii</i>		
<i>Albizia coriaria</i>		<i>Canarium schweinfurthii</i>		<i>Maesopsis eminii</i>	<i>Milicia excelsa</i> <i>Musa paradisiaca</i>		<i>Milicia excelsa</i>
Firewood				<i>Ficus ovata</i>			
<i>Maesopsis eminii</i>	<i>Senna spectabilis</i>	<i>Albizia chinensis</i>	<i>Combretum collinum</i>	Soil moisture			
<i>Albizia coriaria</i>	<i>Albizia zygia</i>		<i>Albizia zygia</i>	<i>Albizia coriaria</i>	<i>Albizia chinensis</i> <i>Musa paradisiaca</i>	<i>Albizia chinensis</i> <i>Musa paradisiaca</i>	<i>Ficus mucoso</i> <i>Ficus sur</i>
<i>Ficus natalensis</i>	<i>Albizia chinensis</i>		<i>Senna spectabilis</i>	<i>Ficus natalensis</i>	<i>Ficus ovata</i> <i>Calliandra calothyrsus</i>		
<i>Milicia excelsa</i>							
<i>Markhamea lutea</i>							
Food							
<i>Musa paradisiaca</i>		<i>Syzygium cumini</i>		Timber			
<i>Artocarpus heterophyllus</i>				<i>Milicia excelsa</i>	<i>Canarium schweinfurthii</i>	<i>Canarium schweinfurthii</i>	<i>Antiaris toxicaria</i> <i>Ficus ovata</i> <i>Ficus mucoso</i>
<i>Carica papaya</i>				<i>Albizia coriaria</i>		<i>Grevillea robusta</i>	
<i>Mangifera indica</i>				<i>Maesopsis eminii</i>			
<i>Persea americana</i>				<i>Markhamea lutea</i>			
Growth rate				<i>Pinus caribaea</i>			
				Yield			

Table 2 continued

Ecosystem service	High PPT zone	Moderate PPT zone	Low PPT zone	Ecosystem service	High PPT zone	Moderate PPT zone	Low PPT zone
<i>Musa paradisiaca</i>	<i>Albizia chinensis</i>		<i>Artocarpus heterophyllus</i>	<i>Ficus natalensis</i>	<i>Albizia chinensis</i>	<i>Albizia chinensis</i>	<i>Ficus mucoso</i>
<i>Carica papaya</i>	<i>Artocarpus heterophyllus</i>		<i>Mangifera indica</i>		<i>Musa paradisiaca</i>	<i>Musa paradisiaca</i>	<i>Maesopsis eminii</i>
<i>Calliandra calothyrsus</i>	<i>Senna spectabilis</i>		<i>Citrus reticulata</i>		<i>Maesopsis eminii</i>		<i>Ficus ovata</i>
<i>Maesopsis eminii</i>	<i>Persea americana</i>		<i>Citrus sinensis</i>		<i>Ficus ovata</i>		<i>Ficus sur</i>
<i>Ficus natalensis</i>			<i>Annona muricata</i>				
Temperature							
<i>Ficus natalensis</i>	<i>Artocarpus heterophyllus</i>	<i>Artocarpus heterophyllus</i>	<i>Ficus mucoso</i>				
<i>Albizia coriaria</i>	<i>Albizia chinensis</i>						
<i>Mangifera indica</i>							
Quick leaf decomposition				Weed control			
<i>Calliandra calothyrsus</i>	<i>Albizia chinensis</i>	<i>Albizia chinensis</i>	<i>Psidium guajava</i>	<i>M. indica</i>	<i>Milicia excelsa</i>	<i>Ficus ovata</i>	<i>Ficus mucoso</i>
<i>Albizia coriaria</i>	<i>Senna spectabilis</i>	<i>Albizia zygia</i>	<i>Senna spectabilis</i>	<i>Artocarpus heterophyllus</i>		<i>Milicia excelsa</i>	
<i>Ficus natalensis</i>	<i>Maesopsis eminii</i>		<i>Persea americana</i>				
<i>Carica papaya</i>	<i>Albizia zygia</i>		<i>Maesopsis eminii</i>	<i>Albizia coriaria</i>			
	<i>Musa paradisiaca</i>		<i>Senna spectabilis</i>	<i>Ficus natalensis</i>			
	<i>Spathodea campanulata</i>		<i>Ficus mucoso</i>				

EC ecosystem services

Fig. 5 Ranking of agroforestry tree species for the provision of quality shade for coffee in the high rainfall zone. (The rectangular marking highlights the most suitable trees for shading coffee in the high rainfall zone, i.e., ecosystem service group of trees)



diversity (Diversity rank) to order ES groups from most to least diverse in each rainfall zone (Fig. 6; Table 3). We found that ‘Diversity rank’ was not significantly correlated with ‘Needs rank’ in any rainfall zones (Fig. 7): on-farm tree diversity of ES groups did not match farmers need for such ES.

Discussion

Tree species composition and diversity

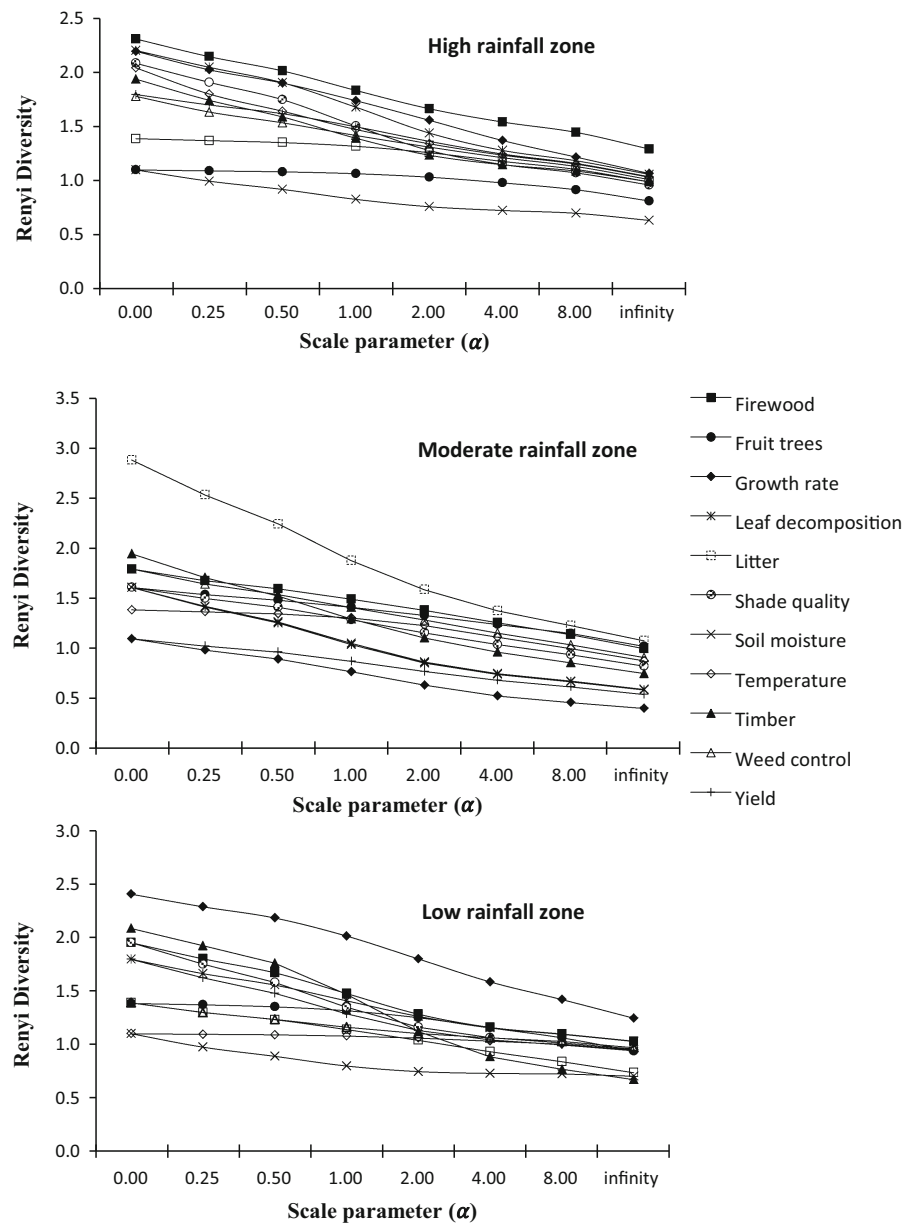
Most tree-diversity studies in agroforestry consider intensification gradients especially with increasing distance from natural forests but this study considered agroforests far from natural forests (no nearby forest) but along a rainfall gradient (Méndez et al. 2007; Valencia et al. 2014; Häger et al. 2015). We found relatively few species, genera, and families per unit area. This is due to the fact that, without a nearby natural forest, farmers entirely rely on and overexploit agroforests and yet re-plant little beyond harnessing natural regeneration (Häger et al. 2015). Low species richness means low functional redundancy implying that minimal losses in species richness will adversely affect ecosystem functioning (Barnes et al. 2014). Along the rainfall gradient, we found higher species

richness in high rainfall zone than in low rainfall zone and species similarity was low among rainfall zones. This is because different rainfall zones support natural regeneration differently which emphasizes the need for deliberate enrichment planting to boost species re-stocking especially in low rainfall zone where natural regeneration of some trees prioritized by farmers may not be as quick as farmers would like it to be (Busby et al. 2010). Increasing species richness will increase ecosystem functioning, functional redundancy, and stability of ES delivery (Gamfeldt et al. 2013; de Beenhouwer et al. 2013; Barnes et al. 2014; Caudill et al. 2014). However, we want to emphasize that increases in tree diversity may not necessarily increase ecosystem functioning unless these increases target tree species suitable for prioritized ES (Radchuk et al. 2015).

Farmers’ local knowledge of trees and the ecosystem services they deliver

Generally ecological conditions, like rainfall, influence tree distribution in coffee agroforestry (Bisseleua et al. 2013). Our findings emphasize this consensus and further demonstrate that relative suitability of trees to deliver ES changes among rainfall zones. For example, diversity data showed that *Ficus mucuso*

Fig. 6 Renyi diversity profiles of ecosystem service groups of trees in three rainfall zones of Central Uganda (ecosystem service group of trees is constituted of trees suitable for providing a particular ecosystem service)



grows in all rainfall zones but only farmers of low rainfall zone ranked it highly among trees suitable for shade quality. Its shade quality is due to its large canopy, but in non-limiting water conditions of high rainfall zone, farmers prefer other tree species such as *Albizia chinensis* that provides better quality shade to coffee even though it needs more water. Furthermore, relative importance of ES changes with rainfall zones. Relative importance of shade and leaf litter increased from high to low rainfall zone. This is because the low

rainfall zone is hotter and coffee needs higher shade level than coffee in high rainfall zone (DaMatta et al. 2007). Farmers also value trees with a lot of leaf litter; an attribute of trees key in nutrient recycling (Dhanya et al. 2013). Therefore, each ecological zone is unique and needs its own tree composition to deliver farmers' prioritized ES.

Past research efforts looked at the provision of ES without jeopardizing yield (de Beenhouwer et al. 2013; Lescourret et al. 2015). This study however

Table 3 Shannon diversity index (H), diversity rank and needs rank of studied ecosystem services in three rainfall zones of Central Uganda

Ecosystem services	High rainfall zone			Moderate rainfall zone			Low rainfall zone		
	H	Diversity rank ^a	Needs rank ^b	H	Diversity rank ^a	Needs rank ^b	H	Diversity rank ^a	Needs rank ^b
Litter	0.32	11	11	1.88	1	8	1.28	7	7
Soil moisture	0.83	10	2	1.05	8	1	1.31	6	2
Food	1.06	9	4	1.41	3	5	1.41	4	5
Timber	1.39	8	10	1.30	6	11	1.16	8	11
Weed Control	1.42	7	9	1.41	4	7	1.47	3	8
Temperature	1.47	6	6	1.31	5	6	1.35	5	4
Yield	1.50	5	1	0.88	10	3	1.47	2	1
Shade quality	1.50	4	5	1.29	7	4	1.14	9	3
Leaf decomposition	1.68	3	3	1.04	9	2	2.01	1	6
Growth rate	1.74	2	8	0.77	11	9	1.08	10	9
Firewood	1.83	1	7	1.49	2	10	0.80	11	10

^aRank of ecosystem service groups of trees according to their tree diversity

^bRank of ecosystem services in order of importance to farmers livelihoods

considered yield increase as one of the many ES rather than one to trade-off with other ES. Farmers' knowledge showed that specific trees suited better than others certain ES. Therefore, we grouped trees according to how well they serve particular ES. Our groupings are consistent with results from previous related studies. For example, our results agree with those of Omeli (2011) showing that leaves from *Ficus natalensis*, *Carica papaya* and *Albizia coriaria* decompose quickly and hence such trees are therefore good for nutrient recycling. Our results also agree with Jagoret et al. (2014) identifying *Milicia excelsa*, *A. coriaria* and *Markhamia lutea* as good timber trees, and those of Kalanzi and Nansereko (2014) showing that *M. excelsa* and *Ficus mucoso* improve soil fertility.

Relating on-farm diversity to farmers' need of ecosystem services

Recognition of farmers' needs and priorities in conservation is gaining adhesion (Harvey et al. 2008; Garcia et al. 2010). We advance the consensus by testing for correlation between farmers' needs (Needs rank) and their on-farm tree diversity (Diversity rank). Farmers' needs did not correlate with on-

farm tree diversity (Fig. 7). Although tree-utility influences tree planting (Valencia et al. 2014; Häger et al. 2015), farmers did not necessarily maintain higher diversity in ES groups of higher priority to them. For example, soil moisture preservation ranked highly among farmers' priority ES but the on-farm diversity of the ES group for 'soil moisture preservation' was low. According to the insurance hypothesis (Leary and Petchey 2009; Mori et al. 2013), ES groups with lower tree diversity are less ecologically stable and render farmers less resilient to challenges like climate change (Tscharntke et al. 2011). Therefore, we emphasize that farmers should base tree diversification on tree-suitability for ES (Fig. 8), particularly for adapting to climate change (Minang et al. 2014).

'FaD–FaN' approach: matching farm tree diversity to farmers' needs

Analysis of previous agroforestry research revealed some research questions that remain unanswered (Mbow et al. 2014b) such as: which tree species suite which site conditions? How can we optimize ES delivery through agroforestry systems? We propose that desired ES can be delivered through optimizing on

farm tree-composition with respect to the suitability of various trees to deliver ES in different environments. This can be achieved through a step-wise approach we refer to as FaD–FaN—farm tree diversity to farmers’ needs at the plot level. The premise of FaD–FaN is that we assessed on-farm tree diversity on one side and farmer’s needs (ES) on the other side. Then we examined whether a particular farmer has the trees that are suitable for providing his/her prioritized ES. If not, then the farmer is advised to adjust his on-farm tree composition to add/increase on trees species suitable for his/her prioritized ES.

In our study, on-farm tree diversity did not match farmers’ need of ES farmers and we recommend increasing on-farm tree Diversity (FaD) to match *Farmer’s Needs* (FaN). The diversity increase could be either species richness or abundance or both. However, the trees to add must be chosen for suitability to provide prioritized ES that has fewer trees on the farm. The FaD–FaN approach, therefore, supports integrating farmers’ needs and priorities in agroforestry designs thereby answering numerous calls for such integration (Harvey et al. 2008; Garcia et al. 2010; Schroth and McNeely 2011; Rey Benayas

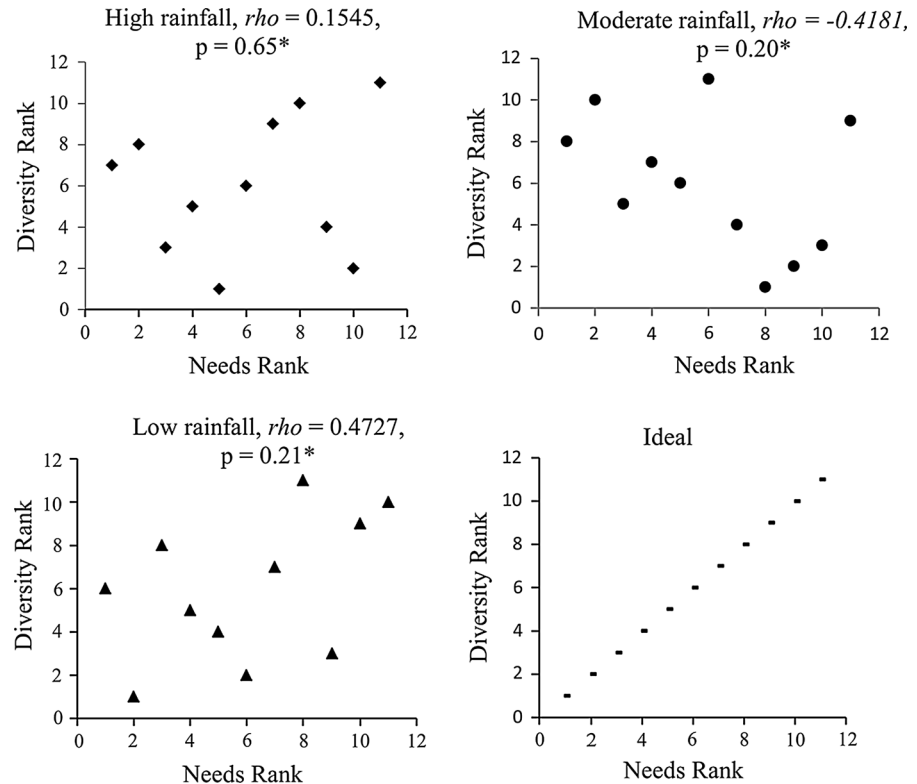
Fig. 8 A conceptual framework of the ‘FaD–FaN’ (matching farm diversity to farmers’ needs) approach for optimizing coffee-agroforestry tree composition for ecosystem service delivery

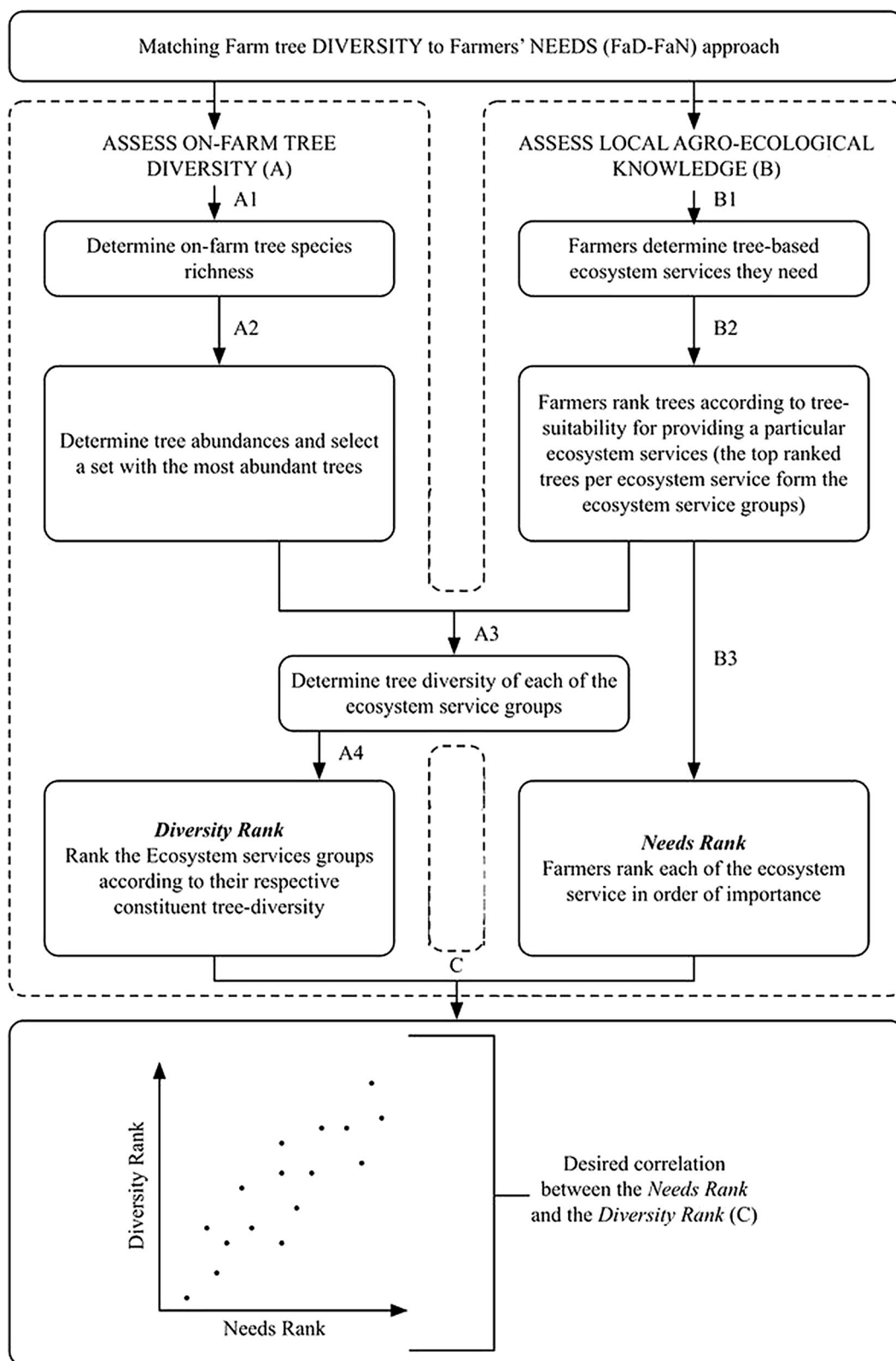
and Bullock 2012). FaD–FaN approach is also a practical instrument for participatory engagement of farmers and scientists to design conservation and agroforestry programs (Lescouret et al. 2015). The implementation of the approach may be aided by a decision support tool (van der Wolf et al. 2016).

Conclusions and recommendations

In the present study, changes in rainfall zones influenced tree diversity, the relative importance of ES and relative tree-suitability for ES delivery indicating that local context underpins appropriate agroforestry designs. Therefore, the FaD–FaN approach advocates for determining tree diversity, the relative importance of ES and relative tree-suitability for ES delivery in each rainfall zone separately. In farms where tree diversity does not match farmers’

Fig. 7 Correlations between ‘Diversity rank’ and ‘Needs rank’ for the three rainfall zones and the ideal situation showing Spearman’s rho and p value for each. Asterisk indicate correlation is not significant, *Diversity rank* rank of ecosystem service groups of trees according to their tree diversity, *Needs rank* rank of ecosystem services in order of importance to farmers’ livelihoods, ecosystem service group of trees is constituted of trees suitable for providing that ecosystem service





prioritized needs, we propose deliberate increases in on-farm tree diversity targeted to boost prioritized ES of currently low tree diversity—cold spot approach (Melián et al. 2015). It is also critical to scale out the development of ‘ES groups’ of trees to other landscapes and socio-economic conditions. These ES groups of trees will underpin tree selection basing on tree suitability for ES.

In this study, farmers’ needs for ES did not match with their on-farm tree diversity; there is need to promote a tree management approach that supports tree diversification with respect to tree suitability for ES—the FaD–FaN approach. To simplify the task of implementing the FaD–FaN approach especially for multiple ES, van der Wolf et al. (2016) presented a decision support tool. Farmers select ES that they need and the tool outputs a set composed of the best-suited tree species at the plot level. Farmers can now optimize their on-farm tree composition for ES delivery in coffee agroforestry. By adopting the FaD–FaN in coffee growing regions beyond the study area, agroforestry will be a step closer to delivering on the promise of improving agricultural livelihoods.

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